FINAL TECHNICAL REPORT

Extending the Earthquake Record on the Southern Santa Cruz Mountains Segment of the San Andreas Fault at the Hazel Dell - Simas Lake Depression: Collaborative Research with the Department of Geological Sciences, University of Oregon, and the California Geological Survey.

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Keywords:

San Andreas fault, Santa Cruz Mountains, earthquake chronology and recurrence

Program Element III

U. S. Geological Survey
National Earthquake Hazards Reduction Program
Award Numbers G13AP00054 & G13AP00055

June 2017

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award numbers Award Numbers G13AP00054 & G13AP00055. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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ABSTRACT

In paleoseismology, contextual information is used to reduce the decade to century ranges in absolute age that result from radiocarbon analytical and calibration uncertainties. This includes the use of historical records, dendrochronology, environmental biomarkers, Bayesian statistical modeling, as well as the removal of apparently inconsistent radiocarbon ages. Excessive ordering constraints and non-unique parameters in paleoseismic age models have resulted in earthquake chronologies that are almost certainly incorrect. Here, we update our Hazel Dell earthquake chronology by adding a wiggle-matched dendrochronological record to constrain the timing of the last three surface rupturing earthquakes. The high precision dendrochronologically constrained age for a paleosol at this site provides an opportunity to evaluate how well materials typically collected for ^{14}C analysis agree with the known age of this soil. We review the usefulness of non-native pollen as a relative age indicators used in age determination models for the Santa Cruz Mountains and broader Monterey Bay area. We collected gouge core samples from a fault-bounded sag pong adjacent to the Hazel Dell site, and find stratigraphic ages agree with the oldest units at Hazel Dell.

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1.0 INTRODUCTION

This report presents age dating results for key stratigraphic units at the Hazel Dell Road paleoseismic investigation site on the Santa Cruz Mountains section of the San Andreas fault, located near the town of Corralitos, Santa Cruz County, California (Figure 1; 37°00'01"N, 121°44'30"W). The objectives of this project were to; 1) refine stratigraphic age models and paleoearthquake timing and recurrence data at the Hazel Dell (HD) site, 2) to evaluate use of relative age indicators such as non-native pollen and its preservation in the sediment record in this forest environment, and 3) to evaluate age ranges for organic samples from a single unit.

This project is a continuation of work in FY2008, FY2010, FY2011, FY2012 at the Hazel Dell site. This grant funded additional work at the Hazel Dell site to refine age estimates for the last four earthquakes at the site. We collected detrital charcoal, and block samples of key stratigraphic units for macrofossil analysis in the lab, and used these samples to constrain the ages of the deposits using ^{14}C dating. In FY2013 we collected samples for analysis of non-native pollen species and abundances from the modern ground soils, surface moss samples, and buried stratigraphic units. We returned in 2012 to re-excavate trenches from 2008 to relocate buried redwood tree stumps identified in FY2008. During the 2012 field season, we exposed shallowly buried redwood stumps at the intersection of trenches T1-T2, and T1-T6 that were 1.75 m wide and were chopped off and burned along the cut face. These stumps were rooted in unit 400, a buried soil and ground surface during the ante-penultimate earthquake, E3. In FY2013 we dated a sequence of annual growth rings from one of these stumps using AMS ^{14}C techniques the results for this effort are reported herein. For additional background information and findings from earlier studies please refer to the Final Technical Report submitted to the U. S. Geological Survey National Earthquake Hazards Reduction Program for Award Numbers G10AP00065, G10AP00064, and G12AP20094, that can be downloaded at: http://earthquake.usgs.gov/research/external/reports/G10AP00064.pdf [Streig *et al.,2014*].

This project originally involved new excavations and coring at an adjacent property to our earlier work (Streig et al., 2014). Due to the sale of this property, twice during the duration of this grant period, we lost access to the original project site. We notified the USGS and modified our project goals which included work described above, additionally we collected and dated samples from one core at the proposed site and find good evidence for high, long-term sediment accumulation rates. We re-evaluate data collected in our earlier Hazel Dell studies, conducted field reconnaissance to evaluate and eventually establish other Santa Cruz Mountains investigation sites, and assisted paleoseismic field work at the nearby Monte Bello site on the San Andreas Fault.

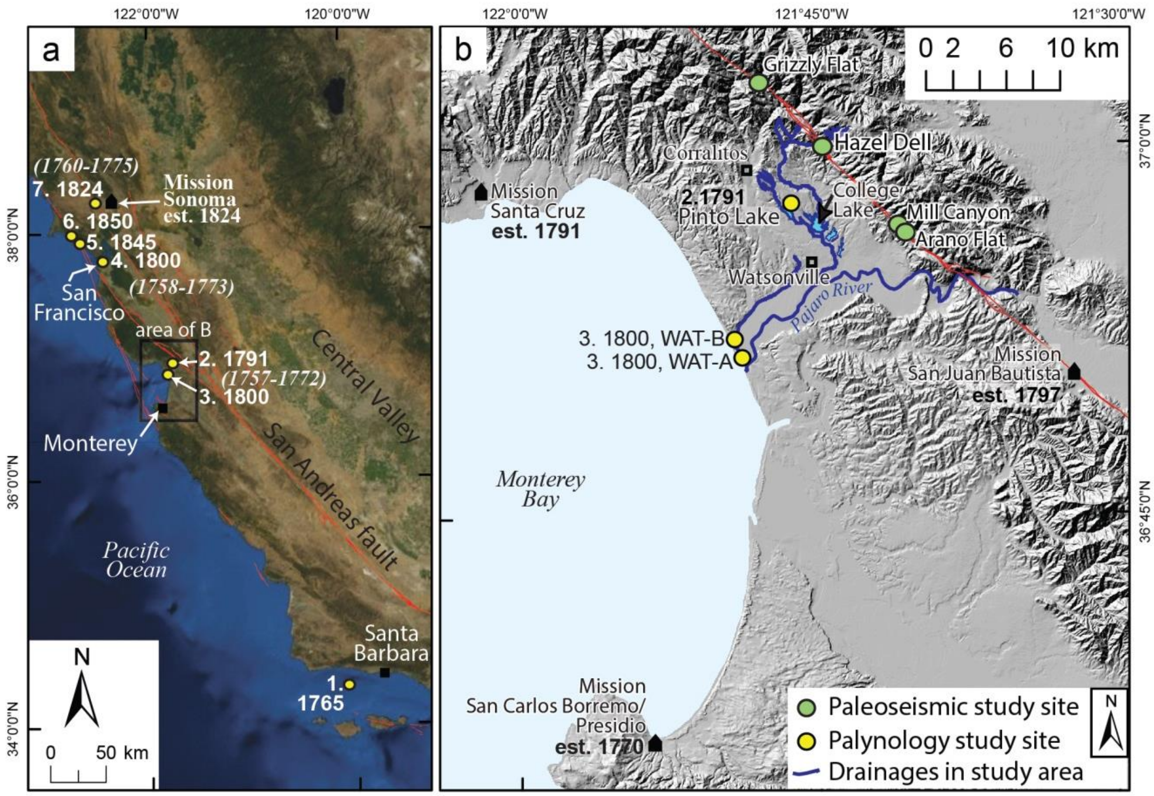

Figure 1. Maps of coastal California showing compilation of Spanish Missions and the year established, and local studies documenting first occurrence of non-native Erodium pollen in sediment record. **a.** Locations of palynology studies (A, yellow circles 1-7) and paleoseismic (B, green circles) sites in coastal California. First occurrence of Erodium pollen in deposits: 1. Santa Barbara, 1750 - 1765, Mensing and Byrne (1998); 2. Pinto Lake, Watsonville, 1791- 1823, Plater et al. (2006); 3. Watsonville slough, 1800 ± 20 years, Byrne and Reidy (2005); 4. Mt. Lake, San Francisco, 1800 ± 20 years, Reidy (2001); 5. Bolinas Lagoon, Marin, 1845 ± 10 years (Byrne et al., 2005); 6. Glenmire, Pt. Reyes, 1850 (Anderson et al., 2013); 7. Triangle G Ranch, Sonoma, 1776 - 1824 (Hecker et al., 2005). White italic text, *(1758-1773)* is the earliest estimated arrival of Erodium for a location using the Mensing and Byrne migration rate of 30 - 50 km/yr. **b.** Paleoseismic and palynology study sites in Monterey Bay Area. Hazel Dell site coordinates are 37°00'01"N, 121°44'30"W. Streams in the Hazel Dell study area watershed and Pajaro River shown are as blue lines. The Hazel Dell stream flows to College Lake, adjacent to Pinto Lake. The first occurrence of Erodium pollen in neighboring Pinto Lake is constrained between 1791 to 1823 [Plater et al., 2006].

2.0 HAZEL DELL ROAD PALEOSESIMIC INVESTIGATIONS

2.1 Hazel Dell Site

At the Hazel Dell paleoseismic site in the Santa Cruz Mountains, CA, the presence of wood chips associated with clearing the redwood forest suggests 3 of 5 early historic earthquakes > M 6 (including well documented 1906 earthquake) occurred here, despite much older detrital charcoal ^{14}C dates (Table 1) and the absence of non-native pollen at these event horizons (Figure 1, Figure 2) [*Streig et al.*, 2014]. A buried soil dated at Hazel Dell and correlated to other nearby sites was faulted in 1906 and two earlier earthquakes (Figure 2) [*Streig et al*., 2014]. In the Santa Cruz Mountains charcoal samples are most often derived from redwoods, which are long-lived trees, leading to great difference, often several hundred years, between detrital charcoal ^{14}C ages and the age of the deposit. As a result, it is generally accepted that at sites where detrital charcoal is the most abundant datable material, success in dating earthquakes relies on analyzing large numbers of radiocarbon samples to identify those samples that are in stratigraphic order [e.g. Rockwell et al., 2015; Scharer et al., 2017; Scharer et al., 2014; Weldon et al., 2004].

In an effort to improve the accuracy of the radiocarbon dates used in Streig et al. [2014] and conclusively demonstrate that the site was logged by early European settlers (a critic might argue that Native Americans logged the site, although there is no record of their felling large redwood trees) ^{14}C "wiggle matching" was applied to a complete slab of a logged redwood tree stump that we excavated from one of our trenches (Figure 2). We use these high-resolution age dates to update modeled ages for the faulted, logged surface, and determine that earthquakes E2 and E3 occurred in the historic period.

Trenches at the Hazel Dell site revealed fine-grained interbedded sand and silt above a buried soil that is faulted in the most recent event, 1906 (not shown here, see *Streig et al*., 2014), and in and two earlier earthquakes (Figure 2). We discovered hundreds of pieces of cut redwood chips coupled with multiple buried redwood tree stumps just below the buried soil, the ante-penultimate (E3) earthquake surface (Figure 2). This demonstrates that the redwood forest at the site was cut down a short time, likely a few years before earthquake E3, and thus E3 must be historic. In our earlier study, we found that E2 has an OxCal modeled age range of 1840 to 1906, and E3 has an age range of 1815 - 1895 (both with 2σ uncertainty) [*Streig et al*., 2014]. These ages are constrained by a historic record of a lumber mill operating in the vicinity by 1832 [*Pybrum-Malmin*, 1998], AMS dates from redwood macrofossils, woodchips, and detrital charcoal. Based on these constraints, E2 and E3 coincide in time with four of the early historic earthquakes in the region, not including 1906 [*Bakun*, 1999; *Toppozada and Borchardt*, 1998].

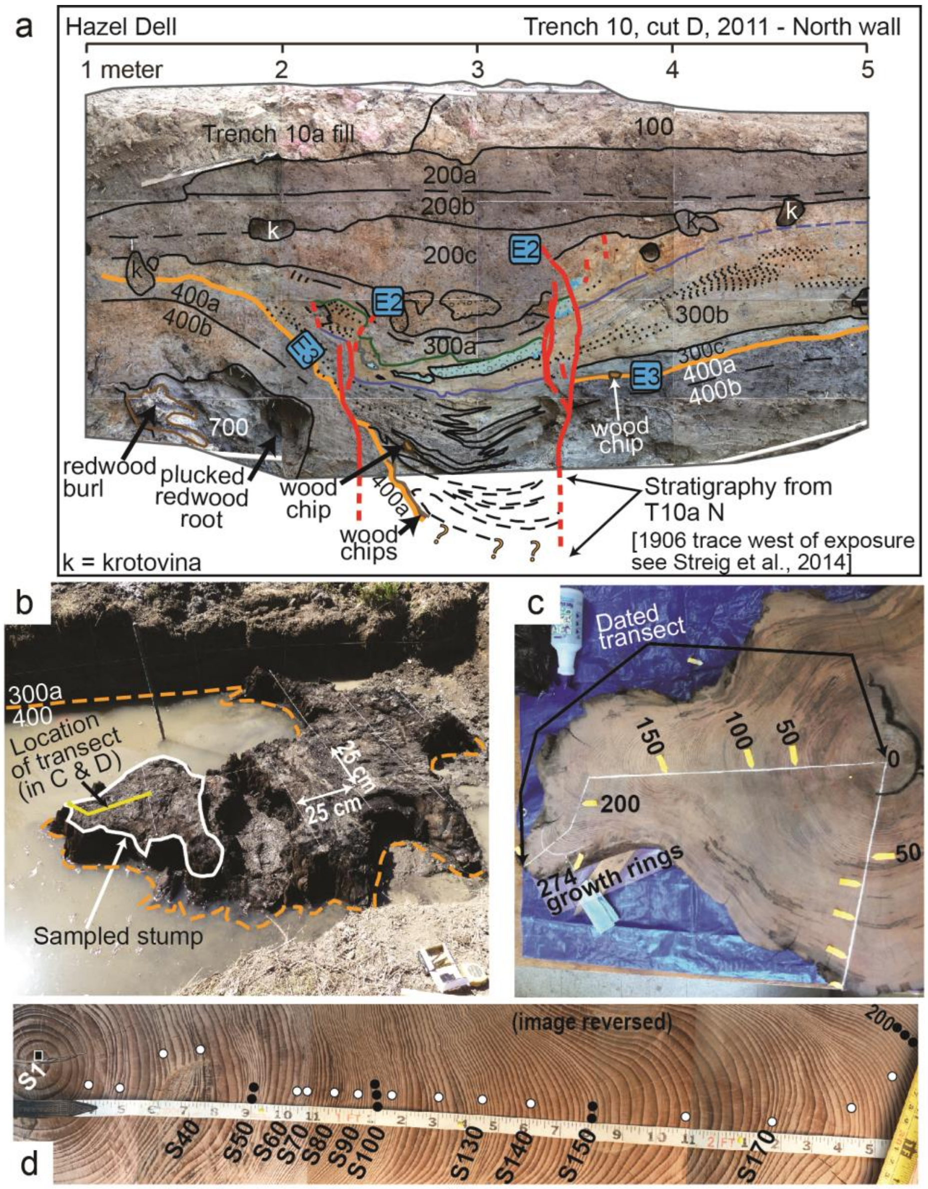

Figure 2. a. Photomosiac log of trench T10D. Showing buried soil unit 400a as a bold orange line, overlain by growth strata units 200 – 300. Wood chips are embedded in the upper horizon of unit 400a, redwood stumps were growning on this surface, the trees and redwood burl are rooted in the horizons below. Red lines are faults, sub-horizontal lines are unit horizons. **b.** Photograph of two buried redwood stumps, 40 - 50 cm below the ground surface at the E3 horizon, Hazel Dell site. Orange dashed line shows the buried unit 400a soil relative to the redwood stump. **c.** The sanded redwood slab with counted tree ring transects shown in white, number of rings shown at the orange arrows. We collected 14 AMS samples from single growth rings distributed roughly evenly from the pith to the outer ring along the long transect. **d**. Polished section of the long transect shown in part b.

2.2 Simas Lake

The Simas Lake depression, approximately 500 meters southeast of Hazel Dell (Figure 3), is located on the seasonally dry margin of a sag pond environment with higher rates of deposition, allowing for better resolution of past earthquakes and likely a longer record of paleoearthquakes. Furthermore, unlike the Hazel Dell site, where radiocarbon samples collected for dating were overwhelmingly dominated by redwood trees with a long residence time and large dating uncertainties, the Simas Lake site is located in a marsh environment. Given the present day distribution of plant species, buried organic materials should be dominated by short-lived wetland plants that form peats, leading to better dating constraints for older earthquakes preserved in the geologic record. We collected gouge core samples from the margin of the lake, and selected 3 organic samples for AMS analysis to evaluate the age – depth relationship of this fault-bound depression.

2.3 Site Geology

The SAF in the Hazel Dell area trends northwesterly, N30°W to N40°W (Figure 3), and bounds the western edge of the valley. Locally, the fault juxtaposes sandstone and shale of the Purisma Formation on the west against shale of the Mt. Pajaro Formation on the east [Brabb, 1989]. Previous workers mapped the SAF as several complex splays; the main trace is characterized by a linear valley, aligned topographic lineaments, offset drainages, linear drainages and sag ponds [Sarna-Wojcicki and others, 1975]. The currently active fault trace is located along the western edge of Hazel Dell Valley, has a relatively continuous surface trace marked by well defined linear base of slope along east-facing hillslopes bounding the valley, and aligned linear drainages and topographic escarpments south of Old Mt. Madonna Road and north of Green Valley Road respectively (Figure 3).

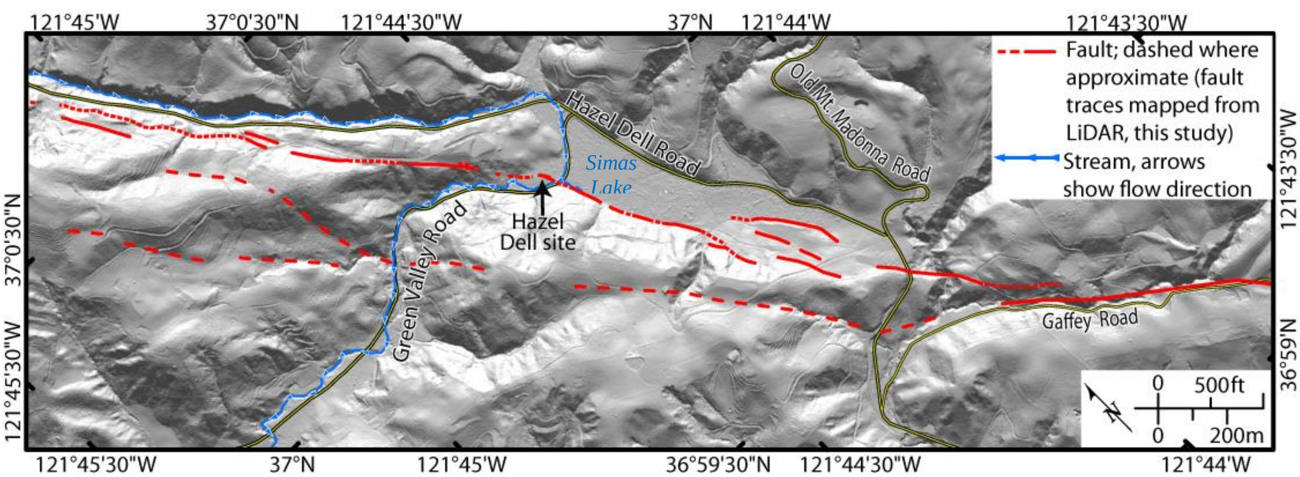

Figure 3. Detailed fault map of geomorphic lineaments in the Hazel Dell area (central SAS) generated from LiDAR data (OpenTopography/ GeoEarthScope 0.5 m data). Locally, the fault is expressed as a series of aligned drainages, linear range fronts , aligned topographic escarpments and a sharp base of slope along east-facing hillslopes. The Hazel Dell investigation site is located in the northwest corner of the fault bound valley, associated with a transtensive (right) step in the fault zone. Simas Lake site is shown by the blue text south of the Hazel Dell site. Fault traces were mapped on 0.5 m resolution LiDAR derivatives in an earlier study (Streig *et al.*, 2012; Streig *et al.*, 2014). Basemap: shaded relief compiled from GeoEarthScope LiDAR data (Prentice *et al*., 2009).

The Hazel Dell trench site is located within an area of overbank deposits on the north side of Green Valley Road, is flanked by Green Valley Creek to the south and west, hillslopes of the sandstone member of the Mt. Pajaro Formation bound the site to the north and east. The creek crosses the fault at the southwest corner of the site (Figure 3). The Hazel Dell site is within the floodplain and has been inundated by flood waters in recent high rainfall years (personal communication, property owner, D. Dent, 2008). In these flood events the site was blanketed by fine-grained alluvial overbank deposits. The investigation site was an apple orchard between roughly 1950 and 1980 (personal communication property owner, D. Dent, 2008). The ground surface has been tilled, disturbing 20 to 50 cm below the ground surface in trench exposures. These farming activities combined with historic overbank deposits obscure the surface expression of 1906 surface rupture across the site. However, 1906 offsets the youngest alluvial units across the site and evidence of the 1906 rupture is preserved in the stratigraphy and exposed in trenches.

We excavated a combination of slot and benched trenches across the site during our field seasons in 2008, 2010, 2011, and 2012 (Figure 4). We collected core samples from the Simas Lake site in 2013 (Figure 4). Trench exposures were cleaned, gridded with a 1 m x 0.5 m string and nail grid, and photographed. All trench exposures were logged on a photo mosaic of high-resolution digital photographs at a scale of roughly 1:10. Stratigraphic units and structural relations were documented and described on photo logs [Streig *et al.*, 2012; Streig 2014]. Both walls were documented in trenches that crossed the fault and fault parallel trenches adjacent to the fault. Only the north wall was documented in trenches 1, 2 and 6 that did not cross a fault trace and were located to span the site to explore for other possible fault traces. We collected detrital charcoal, wood chips, and block samples of key stratigraphic units for macrofossil analysis in the lab, and used all three sample types to constrain the ages of the deposits using ^{14}C dating. During the 2012 field season, we exposed shallowly buried redwood stumps at the intersection of trenches T1-T2, and T1-T6, that were 1.75 m wide and were chopped off. We surveyed trench outlines, faults, string grids and key stratigraphic units using a total station, and used a network of base stations and a differential GPS unit to tie together each survey and incorporate these data in an ArcGIS database (Figure 4).

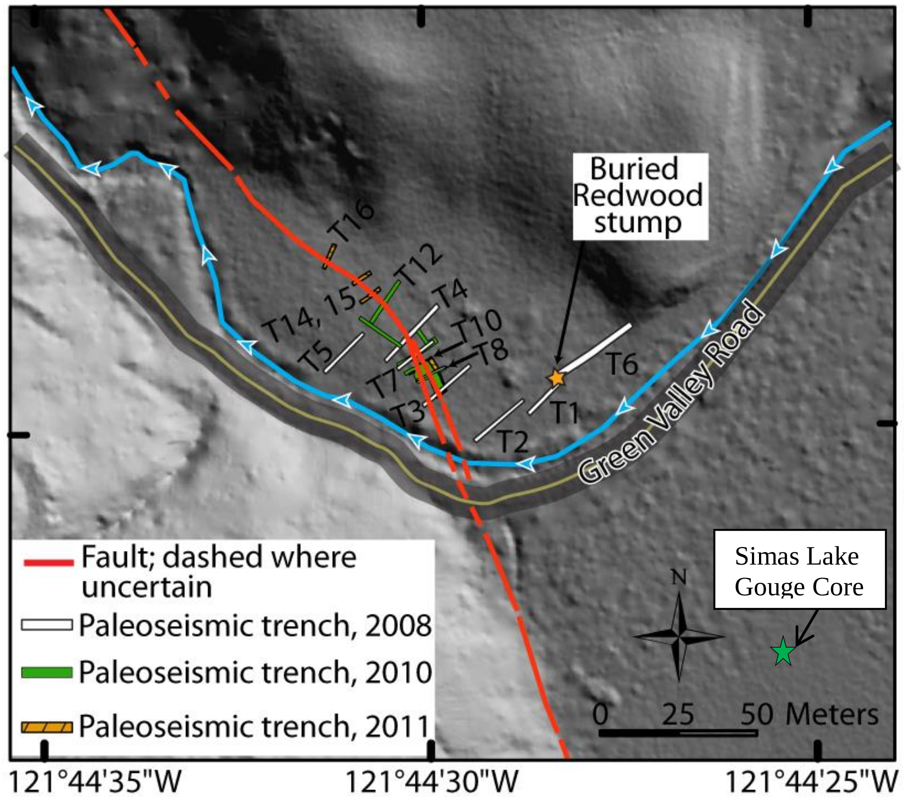

Figure 4. Hazel Dell site map showing the fault trace across the investigation site in red and the locations of 2008, 2010 and 2011 trenches, and the 2012 location of the sampled redwood tree stump. Green Valley Creek is shown in blue; arrows show flow direction. The location of a ~ 1.75 m wide redwood stump is shown by the orange star. Location of the Simas Lake core collected for AMS dating is shown by the green star.

3.0 RESULTS

3.1 ^{14}C Age Dating, Common Problems and Considerations

We recovered an abundance of datable material from stratigraphic units at Hazel Dell, including; detrital charcoal, macrofossils (inferred to be *in situ*), axe-cut wood chips, and logged tree stumps (Table 1; Figure 2). The large abundance of organic material and the buried redwood tree stumps provide a unique opportunity to evaluate how well calibrated ^{14}C ages from organic samples like detrital charcoal, seeds, and wood chips agree with the tightly constrained age of the tree stump. Wood, macrofossils (redwood needles and cone fragments), and selected detrital charcoal samples (generally regarded as the least favorable sample type for dating a layer) were analyzed at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL). We dated 36 radiocarbon AMS samples, of these 3 samples are macrofossils, 15 are detrital charcoal, 4 are from two wood chips, 14 are sequential samples from a buried tree stump (Table 2).

Wiggle Matching Analysis Tree Stump & Wood Chips

The wiggle matching approach compares a series of sequential ^{14}C dates with the known variation in ^{14}C production through time, shown by the INTCAL13 terrestrial ^{14}C calibration curve [*Reimer et al*., 2013] (Figure 5), enough sequential samples spanning the curve yields a unique calendar age. Using the annual interval between samples from the stump, we plot both a visual and Bayesian statistical wiggle-match (OxCal v.4.2.2) [*Bronk Ramsey*, 2017; *Bronk Ramsey*, 2009; *Bronk Ramsey* et al., 2001] for samples spanning 274 tree rings and find, at 2σ certainty, that the outermost ring has an age of 1789 – 1797 (Figure 5; Table 1). In order to account for the possibility that we miscounted or the tree skipped an annual growth ring, we ran a model with ring count uncertainty of +/- 2 years/decade, which we consider to be a high estimate of the uncertainties based on the distinctness of the tree rings in the section (Figure 2). Based on our analysis, we found a 2σ modeled age range of 1779 – 1859 for the outermost ring, which is consistent with the above result. This age range also confirms our hypothesis that early European settlers cleared the site, because the historic era begins in 1770 with settlement of Monterey (Figure 1).

We also wiggle-matched samples from inner and outer growth rings of two wood chips that had preserved bark (Table 1). However, redwood growth is variable around the trunk of the tree so the outer growth ring on a random wood chip may not be from the last growth year of the tree [*Speer*, 2010]. To assess this uncertainty we counted the number of preserved rings in 10 traverses on our tree slab where the bark is preserved and found a range of 32 years for the outer ring. From this data we infer that 11 ± 11 years (1 standard deviation) uncertainty needs to be added to the wood chips outermost ring age to determine its felling age.

The wood chips yield 2σ modeled outer growth ring age range of 1698-1780 (54%); 1804-1850 (41%) for sample HD_2011_WC1 and 1684-1735 (38%); 1756-1785 (8%); 1803-1855 (36%); 1861-1904 (11%) for sample HD_2011_WC2 [*Bronk Ramsey*, 2017; *Streig et al*., 2014]. While these results are consistent with the tree stump, the results are less precise because there are only 2 samples for each wood chip and none landed on a steep or unique portion of the calibration curve. The more conclusive result (HD-2011_WC1) which had 180 years between its two samples, is significant because it also limits E3 to have occurred before 1850, strongly suggesting that E3 is older than the two historic large earthquakes in the late 1800's (1865, 1890), but still yields a broad input to our 2014 age model [Streig et al., 2014].

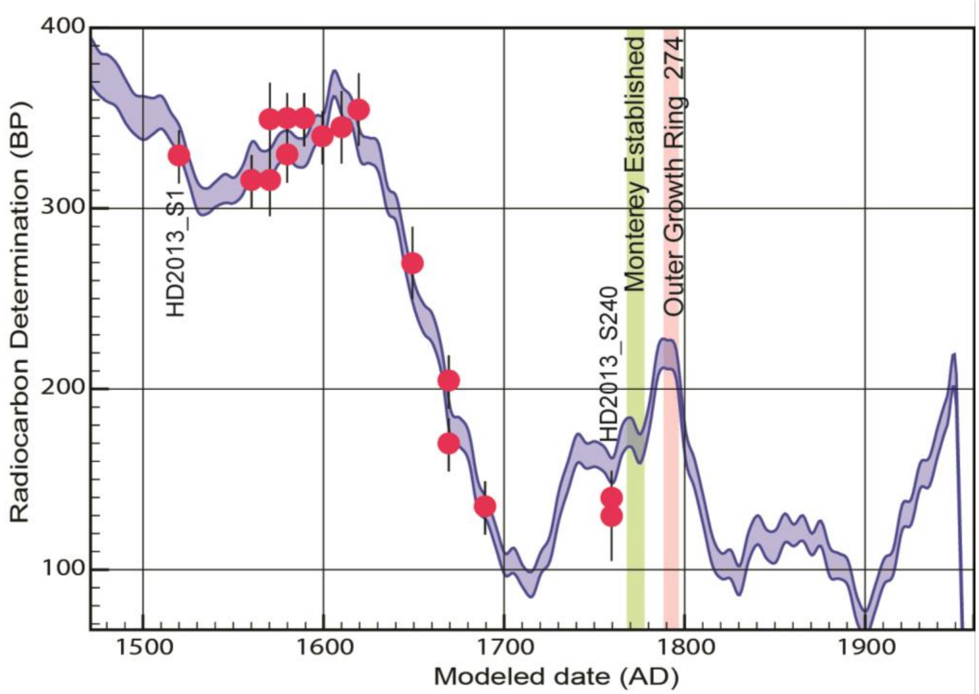

Figure 5. Wiggle match ^{14}C plot of Tree ring ages (Table 1) showing the best fit date of 1789 – 1797 for the outer growth ring of the redwood stump, with ^{14}C ages from the dated transect against the IntCal 13 calibration curve (Reimer et al., 2013). The 2σ modeled age range for the outer growth ring was modeled using D_Sequence, Oxcal v 4.2.2 (Bronk Ramsey, 2017). Red dots show the measured radiocarbon age in years BP, lines are 1σ laboratory uncertainty. The dots are sequential, gaps between samples reflect the interval, or number of growth rings between samples. The oldest sample is the center of the tree, the first growth ring, sample HD2013_S1, where 1 is the order in the tree ring sequence.

Table 1. Radiocarbon Ages for wood chips, redwood cones & needles, and detrital charcoal from the Hazel Dell Paleoseismic site.

Sample Name	Laboratory Number [a]	Unit	^{14}C age [b, c, d, e]	± (1 σ)	Material [f, g, h]	Included in OxCal Model [i]
HD T7-2	Beta-264162	200b	220	40	Charcoal	N
HD T7-7	Beta-254277	200b	350	40	Charcoal	N
HD T7-3	Beta-254274	300a	1150	40	Charcoal	N
HD10a-5-18	CAMS-158276	300c	220	30	Redwood needles	N
HD10a-7-22	CAMS-158277	300c	230	30	Redwood cone fragments	N
HD T8-2	Beta-264164	300c	340	40	Charcoal	N
HD10a-3-28	CAMS-158278	400a Top/ 300c base	190	30	Redwood branch and needles	EQ Model
HD10a-3-28-duplicate	CAMS-158289	400a Top/ 300c base	160	30	Redwood branch and needles	EQ Model
HD-2011-WC-1-A	CAMS-158281	400a Top	280	30	Wood chip, inner growth ring	N
HD-2011-WC-1-B	CAMS-158282	400a Top	130	40	Wood chip, outer growth ring	N
HD-2011-WC-2-A	CAMS-158283	400a Top	115	30	Wood chip, inner growth ring	N
HD-2011-WC-2-B	CAMS-158284	400a Top	185	35	Wood chip, outer growth ring	N
HDT8-40-1	CAMS-158280	400a	350	30	Charcoal	EQ Model
HD T7-5	Beta-264163	400a	340	40	Charcoal	EQ Model
HD T7-1	Beta-264161	400a	590	40	Charcoal	N
HD T7-4	Beta-254275	400a	650	40	Charcoal	EQ Model
HD T7-6	Beta-254276	400a	640	40	Charcoal	EQ Model
HD T8-31	Beta-254278	600b	1250	40	Charcoal	EQ Model
HDT8-32-2008	CAMS-158279	600b	1270	30	Charcoal	EQ Model
HD 4-1	Beta-264157	700a Top	2260	40	Charcoal	N
HD 4-7	Beta-264158	700b Base	2120	40	Charcoal	EQ Model
HD 4-9	Beta-264159	700b Base	2300	40	Charcoal	N
HD 4-12	Beta-264160	900	2710	40	Charcoal	EQ Model
HD2013_S1	161669	Ring 1, innermost ring. Pith.	350	20	GR	D Model
HD2013_S1 duplicate	161670	Ring 1, innermost ring. Pith.	350	20	GR	D Model
HD2013_S40	161671	Ring 40	330	20	GR	D Model
HD2013_S50	161672	Ring 50	330	20	GR	D Model
HD2013_S50 duplicate	161673	Ring 50	365	20	GR	D Model
HD2013_S60	161674	Ring 60	350	20	GR	D Model
HD2013_S60 duplicate	161675	Ring 60	370	20	GR	D Model
HD2013_S70	161676	Ring 70	365	20	GR	D Model
HD2013_S80	161677	Ring 80	360	20	GR	D Model
HD2013_S80 duplicate	161678	Ring 80	335	20	GR	N
HD2013_S90	161679	Ring 90	365	20	GR	D Model
HD2013_S100	161680	Ring 100	375	20	GR	D Model
HD2013_S130	161681	Ring 130	285	20	GR	D Model

Table 1. Radiocarbon Ages, *continued.*

HD2013_S140	161682	Ring 140	210	20	GR	N
HD2013_S150	161683	Ring 150	215	20	GR	D Model
HD2013_S150 duplicate	161684	Ring 150	180	20	GR	D Model
HD2013_S170	161685	Ring 170	190	20	GR	N
HD2013_S170 duplicate	161686	Ring 170	145	20	GR	D Model
HD2013_S240	161687	Ring 240	145	25	GR	D Model
HD2013_S240 duplicate	161688	Ring 240	155	20	GR	D Model
HD2013_S271	161689	Ring 271, near bark.	730	20	GR	N
HD2013_S271 duplicate	161690	Ring 271, near bark.	260	20	GR	N

Notes:

a) Samples processed at Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory, and at Beta Analytic Inc., Florida (Beta).

b) Preliminary ^{14}C ages, a d13C value of -22 was used as the assumed value for all samples according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977).

c) The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (1977).

d) Radiocarbon concentration is given as conventional radiocarbon age.

e) Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free wood.

f) Sample Material: GR = Growth ring from redwood tree stump. Backgrounds were scaled relative to sample size.

g) Tree ring samples from the redwood stump were pretreated with acid-alkali-acid washes, the final acid wash was a wet oxidation step (0.1 molar K2CrO5 + 2 molar H2SO4) to remove translocated folic acid/cellulose between growth rings and minimize measured age uncertainty.

h) Wood chip samples underwent standard acid-alkali-acid pretreatment and did not undergo wet oxidation.

i) Samples retained in OxCal Earthquake model (EQ model), or Dendrochronologic Wiggle-match model (D Model). N, sample not retained in model.

Table 2. Table of OxCal Dendrochronologic Wiggle Match for Growth Rings Sampled From a Buried Redwood Tree Stump. Table Results from OxCal Dendrochronologic Wiggle Match Model Calibrated modeled age ranges are shown as both 68.2% (1σ) and 95.4% (2σ). Gaps represent the number of annual growth rings (years) between samples.

Tree Ring Sample & Interval	OxCal Modelled Ages (BC/AD)			
	68.20%		95.40%	
	from	to	from	to
Boundary E1 - 1906				
Outer Growth Ring - Ring 274	1791	1795	1789	1797
Gap 34 years				
R_Combine S240	1757	1761	1755	1763
Gap 70 years				
R_Date HD-2013-S170dup	1687	1691	1685	1693
Gap 20 years				
R_Combine S150	1667	1671	1665	1673
Gap 20 years				
R_Date HD-2013-S130	1647	1651	1645	1653
Gap 20 years				
R_Date HD-2013-S100	1617	1621	1615	1623
Gap 10 years				
R_Date HD-2013-S90	1607	1611	1605	1613
Gap 10 years				
R_Date HD-2013-S80	1597	1601	1595	1603
Gap 10 years				
R_Date HD-2013-S70	1587	1591	1585	1593
Gap 10 years				
R_Combine S60	1577	1581	1575	1583
Gap 10 years				
R_Combine S50	1567	1571	1565	1573
Gap 10 years				
R_Date HD-2013-S40	1557	1561	1555	1563
Gap 40 years				
R_Combine S1	1517	1521	1515	1523
D_Sequence Wiggle-match stump				

Detrital Charcoal and Macrofossils

At Hazel Dell, we dated 15 detrital charcoal samples and found 8, or 53%, to be stratigraphically consistent within the section exposed in the trenches (Table 2) [Streig et al., 2014]. At sites surrounded by longer-lived species, detrital charcoal has larger "in-built" ages (essentially the difference between the time since wood-formation and the fire that generated the charcoal) [*Gavin*, 2001]. If one knew the full spread of ages from a given unit, and the age range of the representative species, one could evaluate the true age of the burn event that generated the charcoal [*Gavin*, 2001]. However, from a practical point of view one could take the youngest sample from a series of overlapping ages collected from a unit as the closest to the true age of the unit.

In-built age can be reduced by sampling fragments from short-lived species (i.e. chaparral), twigs or identifiable organic remains (i.e. "macrofossils" like seeds, needles, cones). It seems reasonable that macrofossils should have shorter residence times at the surface and be less susceptible to reworking, so paleoseismologists increasingly focus on such samples (Table 1). At Hazel Dell we dated 3 macrofossil samples from block samples of the stratigraphy that immediately post-dates earthquake E3. Using a microscope we collected redwood cone fragments, delicate redwood needles and a redwood branch with needles still attached (Streig et al., 2014; Table 1, samples HD10a-7-22, HD10a-5-18, HD10a-3-28 respectively). Of these, only the branch with attached needles (HD10a-3-28) was stratigraphically consistent; the other two macrofossil samples were above this sample, but yielded older calibrated ages that were inconsistent with the branch, wood chips, and logged tree stump. Macrofossils were collected from finely laminated sediments that preclude the possibility of subsequent bioturbation; the redwood cone fragments and needles were unquestionably recycled. Similarly, at Wrightwood, CA on the southern San Andreas, Biasi et al. [2002] report that pinecone macrofossils had large inherited ages that were inconsistent with other detrital samples and *in situ* peat dates. We conclude that macrofossils require the same consideration as other detrital radiocarbon samples and should be similarly scrutinized for consistency.

We plot calibrated ^{14}C ages for the E3 buried soil (unit 400a) at Hazel Dell, which has a precise age from the wiggle-matched redwood stump. Figure 6 shows a 130 year lag between the time the Hazel Dell site was logged and probability distribution functions (pdf's) for the youngest detrital charcoal samples collected from the corresponding ground surface (unit 400a top). The 130 year offset between the timing of logging at the site and these pdf's highlight the difficulties of sampling and dating charcoal that formed within a few decades of the event of interest, the top of unit 400a. Prior to having the tree stump and wood chip high precision calibrated ages, we used charcoal samples to constrain the age of the surface, these samples clearly have either in-built ages or a residence time that is 130 years greater than the event we are trying to date. As a result early age models developed using preliminary charcoal dates yielded broad pre-historic age ranges for earthquakes E2 and E3 at Hazel Dell, which we now know to be incorrect.

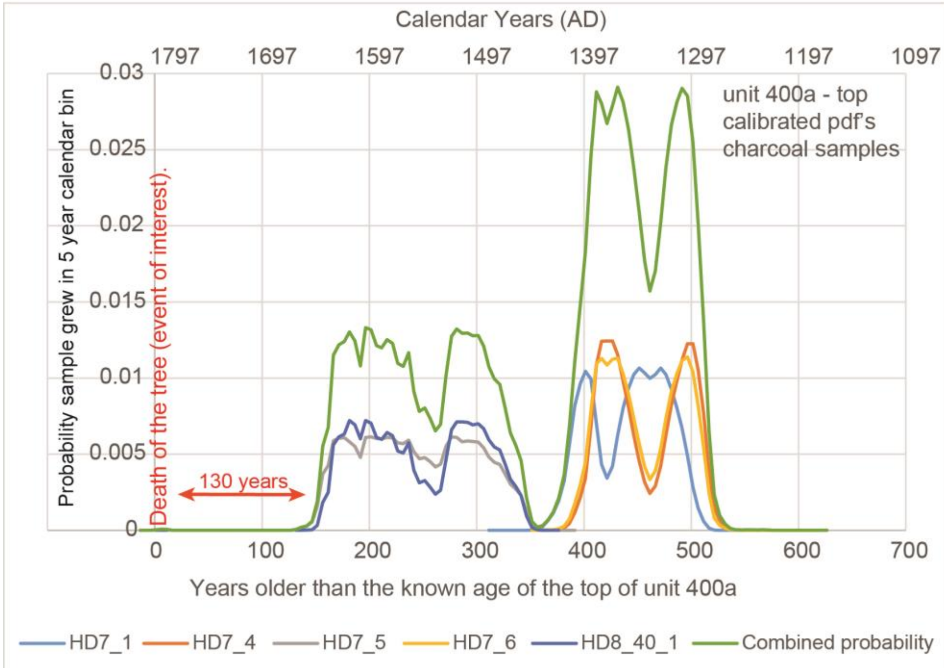

Figure 6. Stacked plot showing calibrated pdf's for 5 detrital charcoal samples collected from the top of unit 400a, which was the ground surface at the time the redwood trees were chopped down. Death of the redwood tree is dated between 1789-1797 (see Figure 5). The youngest charcoal dated from unit 400a is 130 years older than the surface we are trying to date. Calendar year 1797 was subtracted from each 5 year binned calendar age for the calibrated probability distribution functions for each detrital charcoal fragment sampled from the unit 400a paleo-ground surface to evaluate number of years charcoal formed before the unit we are trying to date, the top of unit 400a.

Detrital Charcoal from the Simas Lake Core

We selected organic samples from a gouge core at Simas Lake for AMS analysis. Of these, two samples were run with typical acid-base-acid pretreatment, one sample (HDS-6) was split and pretreated with acid only. Two samples yielded similar calibrated age results; HDS-3-AO treated with acid only to remove acid soluble organics, and HDS-3-ABA pretreated with full acid-base-acid sequence. These samples yielded a 2σ calibrated age of 1270 to 1390 AD and 1286-1405 AD, respectively. These ages are consistent with unit 400 at the Hazel Dell site. The split for sample HDS-6 that was also pretreated with full acid-base-acid sequence yielded an age that was inconsistent with the other two (Figure 7; Table 3). This inconsistent sample, HDS-6-ABA, resulted in an older 2σ calibrated age range of 883 – 1012 AD.

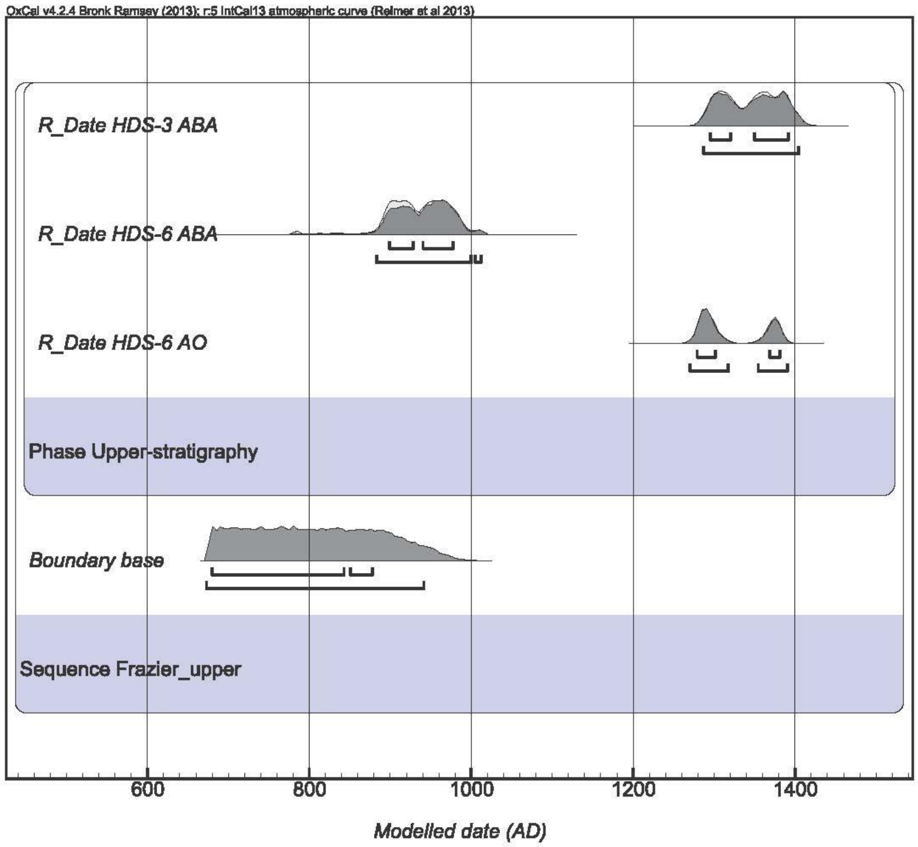

Figure 7. OxCal Age Model for gouge core collected from Simas Lake. Prior Probability distribution functions (pdf's) for calibrated radiocarbon samples shown in light gray, posterior pdf's determined using ordering information shown in dark gray. Unit numbers are shown on the shaded bars.

Table 3. Radiocarbon Ages for organic samples collected from the Simas Lake gouge core.

									Calibrated Ages			
Sample Name	**CAMS #**	**d^{13}C**	**fraction Modern**	**±**	**D^{14}C**	**±**	**^{14}C age**	**±**	1σ Age Range (BC/AD) from	1σ Age Range (BC/AD) to	2σ Age Range (BC/AD) from	2σ Age Range (BC/AD) to
HDS-6 AO	CAMS-166541	-25	0.9189	0.0030	-81.1	3.0	680	30	1279	1381	1270	1390
HDS-6 ABA	CAMS-166544	-25	0.8709	0.0031	-129.1	3.1	1110	30	895	976	879	1013
HDS-3 ABA	CAMS-166543	-25	0.9253	0.0044	-74.7	4.4	625	40	1295	1393	1286	1405

1) δ^{13}C values are the assumed values according to Stuiver and Polach (Radiocarbon, v. 19, p.355, 1977) when given without decimal places. Values measured for the material itself are given with a single decimal place.

2) The quoted age is in radiocarbon years using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (ibid.).

3) Radiocarbon concentration is given as fraction Modern, D^{14}C, and conventional radiocarbon age.

4) Sample preparation backgrounds have been subtracted, based on measurements of samples of ^{14}C-free coal. Backgrounds were scaled relative to sample size.

5) AO designates samples that were only pretreated with acid (to remove fulvics, acid soluble organics) as per requested. ABA is full acid-base-acid pretreatment.

3.2 Non Native Pollen as a Relative Age Indicator, Uses and Considerations

The first appearance of pollen from exotic species, such as *Eucalyptus*, *Erodium cicutarium*, *Rumex* and *Plantago* in California, can reveal the onset of European settlement and related major land use changes [*Anderson et al*., 2013]. *Erodium cicutarium* is the most common exotic pollen source used as a relative age indicator by paleoseismologists in California [e.g. *Fumal*, 2012; *Fumal et al*., 2003; *Hecker et al*., 2005; *Lienkaemper et al*., 2002; *Lienkaemper and Williams*, 2007; *Schwartz et al*., 2014]. *Erodium* was introduced by the Spanish (first identified in cores from the Santa Barbara Basin dated around 1750 – 1765), preceding significant Spanish settlement in California [*Mensing and Byrne*, 1998]. Mensing and Byrne [1998] estimate a 30 to 50 km/yr *Erodium cicutarium* migration rate across the California grasslands. This rate is frequently used as a first-order age estimate for the stratigraphic horizon containing the first occurrence of *Erodium cicutarium* pollen for California paleoseismic sites. It has also been used to argue that key sediment layers lacking non-native pollen preceded European settlement, and consequently an earthquake within stratigraphy lacking this pollen has been considered pre-historic. When these assumptions are applied as historical constraints with little to no uncertainty in age models they force what could be historic stratigraphy into the prehistoric period.

Erodium cicutarium is a problematic biomarker that is generally suited only to grasslands and is not found in forest shade [*McLaughlan and Clark*, 2004]. It has low pollen production and dispersion, and has heavy seeds that are primarily dispersed by water transport and animal migration [*Mensing and Byrne*, 1998]. Additionally, geologic (i.e. depositional setting), geographic (climate, topographic relief) and biologic (landscape openness) factors all contribute to pollen preservation and abundance in deposits and thus the success in applying this technique as an age indicator in paleoseismic studies. All of these factors impact the arrival of *Erodium cicutarium* and preservation of its pollen in the stratigraphic record.

Non-native Pollen Analysis in the Greater Monterey Bay, CA

The first occurrence of *Erodium cicutarium* in the Monterey Bay area is historically constrained to the early 19th Century [*Plater et al*., 2006; *Byrne and Reidy*, 2005; *Hendry*, 1925), later than the estimated arrival ~1770 from the migration rate [*Mensing and Byrne*, 1998]. Cores from Pinto Lake show the first occurrence of *Erodium cicutarium* pollen in the period between 1791 to 1823 [*Plater et al*., 2006], 20 to 50 years later than the estimated arrival date, and at least 20 years later than the first documentation of cattle and horse grazing in the region in 1807 [*Pybrum-Malmin*, 1998]. This is the nearest pollen study to the Hazel Dell, Arano Flat, and Mill Canyon paleoseismic sites (Figure 1). A marsh core study in the Watsonville Slough (Figure 1) finds *Erodium cicutarium* at a depth of 100 cm, the authors assign a date of 1800 ± 20 years to this horizon. This date is inferred and is based on an earlier study of *Erodium cicutarium* macrofossil remains in adobe bricks at Mission San Juan Bautista, established in 1797 (Figure 1) [*Byrne and Reidy*, 2005; *Hendry and Kelley*, 1925].

The first occurrence of *Erodium cicutarium* in the greater San Francisco Bay region, generally from 1770 to 1860 (Figure 1), is also several decades later than estimated using the Mensing and Byrne [1998] migration rate. A core at Mountain Lake in San Francisco finds the first occurrence of *Erodium cicutarium* around 1800 ± 20 years (Figure 1)

[*Reidy*, 2001], and is within the same range as Monterey Bay. On the north side of San Francisco Bay, a marsh core study at Bolinas Lagoon finds the first occurrence of *Erodium cicutarium* appears just before 1850 (Figure 1) [*Byrne et al.*, 2005]. A second core site, at Glenmire, in Pt. Reyes (Figure 1), dates the first occurrence of exotic Plantago grass, to 1850, and the first occurrence of *Erodium cicutarium* is stratigraphically above (younger than) that horizon (Figure 1) [*Anderson et al.*, 2013].

Non-native Pollen Analysis at the Hazel Dell Site

The Hazel Dell site lacks exotic pollen in historic sediments, but these sediments also have poorly preserved pollen abundance from native plant species (Figure 8; Table 4). Poor pollen preservation might be the cause for lack of exotic pollen, but paleoseismic studies rarely report abundance. The first occurrence of *Erodium cicutarium* in the Monterey Bay is historically constrained to the early 19th Century [*Byrne and Reidy*, 2005; *Plater et al*., 2006], later than the estimated arrival ~1770, from the migration rate from Santa Barbara [*Mensing and Byrne*, 1998]. In the greater San Francisco Bay region, *Erodium cicutarium* first appears in horizons ranging from 1770 to 1860 (Figure 1), which is several decades later than estimates using the migration rate (Figure 1) [*Reidy*, 2001; *Anderson et al*., 2013].

Considerations for use of Non-native Pollen in Age Models

Our work and other regional studies (e.g. Fumal, 2012; Hecker et al., 2005) highlight that the measured and historically constrained ages of the horizon associated with the first appearance of *Erodium cicutarium* in this part of California is almost always several decades later than the estimated arrival based on modeled migration rates (Figure 1). This study, and other sites in the vicinity of Hazel Dell (Fumal, 2012; Fumal et al.,2003; Schwartz et al., 1998), show that *Erodium cicutarium* is a difficult biomarker to find, especially in forest soils. Without additional local palynology and paleo-environmental studies to assess the suitability of the site for colonization and preservation of *Erodium cicutarium*, the migration rate proposed by Mensing and Byrne (1998) should be used only as a lower limit for the timing of the first stratigraphic occurrence of the exotic pollen**.**

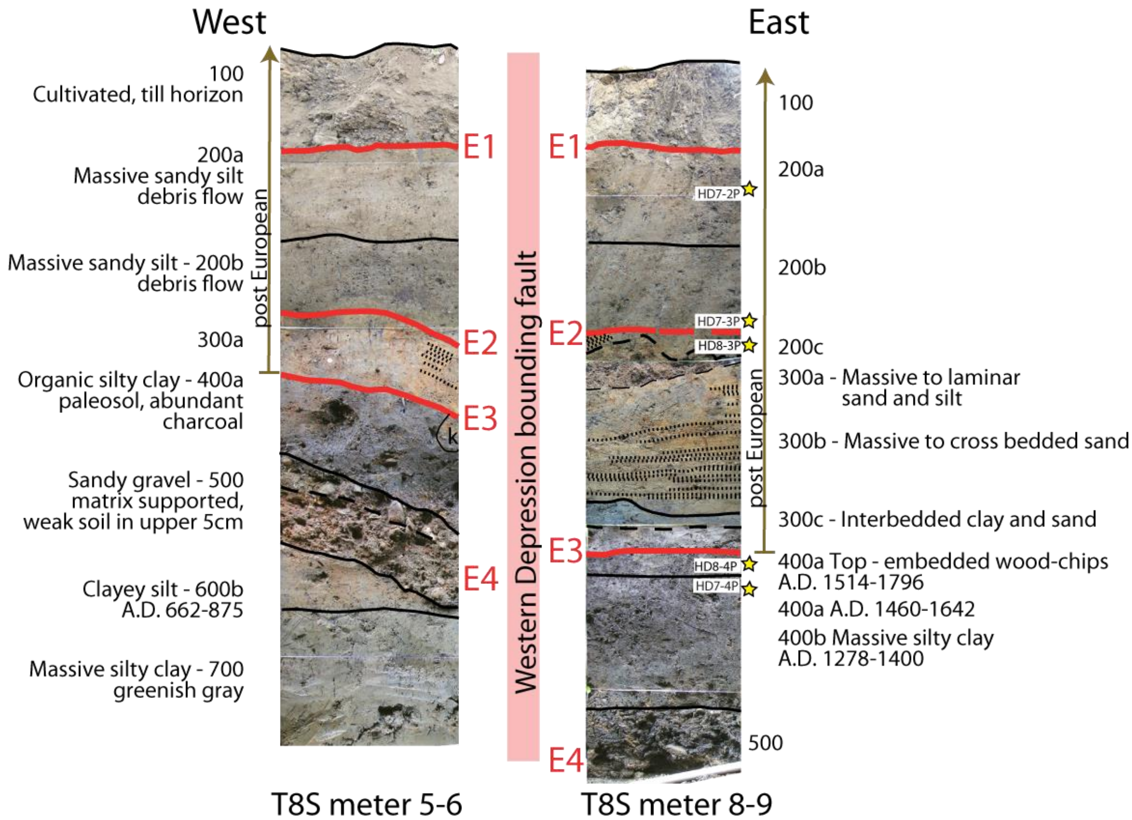

Figure 8. Stratigraphic sample locations for pollen analysis at HD, results shown in Table 4. Stratigraphic sample locations for pollen analysis at HD. Photomosaic stratigraphic columns correlated between East and West sides of the primary Western depression bounding fault. Black lines are unit contacts, shaded lines labeled E1 through E3 are earthquake horizons. Yellow stars show units sampled for non-native pollen analysis, sample name (eg. HD8-3P) denotes study site (HD), Trench number (8), and pollen sample number in that trench (3). Two sigma modeled age ranges for units shown in years A.D.

Table 4. Pollen concentrations for three pollen samples shown in Figure 7. Pollen concentrations are generally less than 500 grains/cm3, so it is not possible to conduct pollen analysis. Standard samples have at least 10,000 grains per cm3. The soil sampled in the Hazel Dell trenches is generally "sterile" of pollen.

Pollen counts for Non-Native Pollen Analysis at HD

Hazel Dell Pollen samples			
	HD7-2P	**HDT8-3P**	**HD7-4P**
Date counted	4-Feb-14	4-Feb-14	17-Feb-14
Pollen			
Cyperaceae	1	2	
Pinus		1	1
Poaceae		1	1
Quercus		1	
Sequoia		1	
Pseudotsuga		2	
Cupressaceae		1	
Pollen sum	1	9	2
Spores			
Monolete	5	6	5
Trilete	2		3
Exotic lycopodium	155	80	80
Volume (cm3)	1.23	1.23	1.23
Spores/tablet	13911	13911	13911
Number of tablets	1	1	1
Pollen concentration (grains/cm3)	73	1272	283
Errors are +/- 5%			
Samples analyzed by Dan Gavin, UO			
Samples prepared by Liam Riedy,UCB			

4.0 SIGNIFICANCE OF RESULTS

We update our Hazel Dell earthquake chronology by adding a wiggle-matched dendrochronological record that conclusively constrains the timing of the last three surface rupturing earthquakes to the 19th and early 20th centuries. We interpret the most recent event, E1, to be the 1906 surface rupture. We conclude that two surface rupturing earthquakes occurred on the Santa Cruz Mountains section of the San Andreas fault in a 68 year period preceding the 1906 earthquake, the M ~6.6 1838, and M ~6.8 -7.2 1890 earthquakes (Figure 9). The most recent pre-historic surface rupturing earthquake, identified at the Arano Flat site [Fumal et al., 2003], precedes these ruptures by 100 – 200 years. The high precision dendrochronologically constrained age for a paleosol at this site allowed us to evaluate how well organic material typically collected for ^{14}C analysis agree with the known age of this soil. We found large residence times and in-built ages for detrital charcoal samples. We suggest dating multiple samples from a given unit and using the youngest ages in an age model.

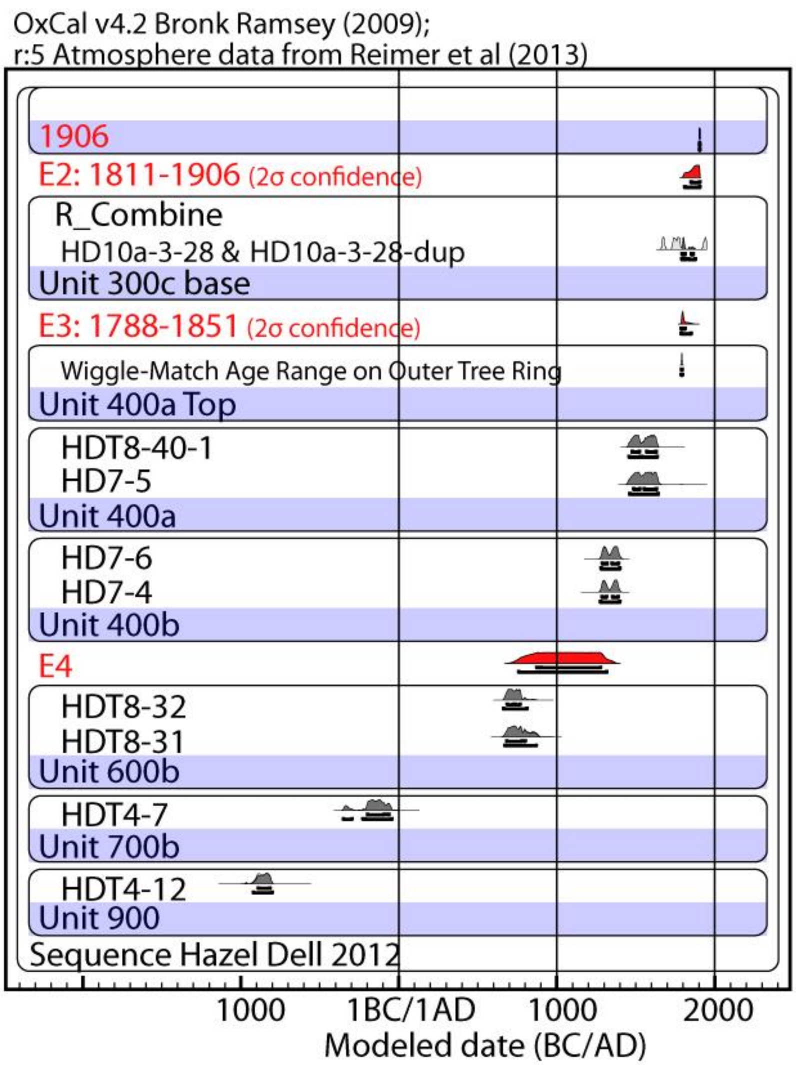

Figure 9. Updated OxCal Model with New Age Results from Redwood Stump Wiggle Match and Macrofossils. Updated OxCal model of stratigraphic units and earthquake age estimates for the Hazel Dell site. Prior Probability distribution functions (pdf's) for calibrated radiocarbon samples shown in light gray, posterior pdf's determined using ordering information shown in dark gray. Unit numbers are shown on the shaded bars. Modeled earthquake ages are labeled by event name. Note – inconsistent samples removed, see Table 1 for a complete list of samples.

5.0 ACKNOWLEDGEMENTS

The authors would like to thank the property owner David Dent for allowing us to work on his property and for his continued interest in our results. We thank Carol Prentice, David Schwartz, Suzanne Hecker, Gordon Seitz, Ron Rubin, Andy Lutz, and Steve Thompson for their thoughtful field review and insightful discussion of event evidence at in the field during the many field seasons of field work. We thank Rachel Lippoldt, Courtney Streig, Nyle Weldon, and Spencer Kendall for their assistance in the field, and Jan and Dave Streig for logistical support.

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